A METHOD FOR ERROR REDUCTION IN LITHOGRAPHY

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation-in-part of co-pending Application No. 09/979,148, filed on November 20, 2001 and for which priority is claimed under 35 U.S.C. § 120. Application No. 09/979,148 is the national phase of PCT International Application No. PCT/SE00/01030 filed on May 22, 2000 under 35 U.S.C. § 371. This application also claims priority of Application No. 9901866-5 filed in Sweden on May 20, 1999 under 35 U.S.C. § 119. The entire contents of each of the above-identified applications are hereby incorporated by reference.

Field of the invention

The invention relates to production and precision patterning of photomasks and use of such photomasks in microlithography, for example in the production of flat panel displays and semiconductor circuits. Errors in the pattern on the display panel or semiconductor chip can be separated into errors from systematic sources, from the interaction of maskblank and pattern with the equipment, and from random fluctuations. The invention relates to the reduction of these errors. In a different sense the invention relates to the characterization of the photomask substrate and the equipment and processes used with a photomask, the storage and retrieval of information obtained by such characterization, and the generation of corrections to be applied at the time of writing the photomask in order to reduce imperfections in lithography using photomasks.

Background

The development of semiconductor lithography has been exponential since the early 60ies and the produced features are getting smaller every second or third year,

at the same time as the circuits get faster and more complex. Figure 1 shows an industry projection of the development for some years forward. Of course the predictions are less certain the farther into the future we look and nobody knows if the electronics industry will still be using transistors in the year 2020. For the next 10 years the projections are more certain and the main uncertainty relates not to "How small?" but to "Exactly when?".

The errors in lithography can broadly be classified as placement and size errors, or "registration" and "critical dimension", ("CD") in the jargon of the trade. There is a more or less fixed relation between the errors that can be allowed in the pattern and the size of the smallest features in the pattern. A rule of thumb is that on the mask the placement of figures has to be within 5% of the design rule and the size of the features should be within 2.5%. These are surprisingly small numbers, but have been justified by both theory and experiments. Figure 1 also shows the necessary registration and CD (size) control on the mask for each year, assuming that 4X masks will continue to be used. It is seen that the errors are now 1999 in the low tens of nanometers and will in less than 15 years be ten times smaller. At the same time then chips will be larger which means either larger masks or less reduction. Either way it will be difficult to achieve the needed pattern fidelity.

The invention devises a new general method to reduce errors in the lithography in order to achieve total errors that are consistent with the projected lithography development. An important application is for the reduction of clamping errors, being both an important error source and a good example of errors caused by the interaction of several factors.

Clamping errors

When a glass plate is held it is deformed by the holding device and by its own weight. Furthermore, it can

also be distorted by the built-in stress in surface films deposited on it and by the patterning of said films. Semiconductor masks are typically 152 x 152 x 6.25 mm and the patterned area may be 127 x 127 mm. Figure 2b shows how the bending of a plate 201 under the force of gravitation causes the upper area of the glass to contract. When the plate is released, e.g. held vertically, it springs back to its natural shape, shown in fig 2a, and contraction disappears. If a pattern was written on the plate while it was bent, the pattern will be stretched after relief. Figure 3 shows a diagram with the resulting maximum error when a plate is supported along two opposite edges, as in fig 2. Here, the expected lateral position error is shown as a function of the thickness of the plate and the size, i.e. the distance between the two supported sides. The interesting conclusion from Figure 3 is that the magnitude of errors that can result from inappropriate support of a glass plate is in order of magnitude larger than what is allowable in a high-end mask. Point A shows a standard semiconductor reticle 152 x 152 x 6.25 mm and the maximum deviation is around 400 nm. Point B is the new standardised mask format 225 x 225 x 9 mm and, despite the fact that the glass plate is thicker, the deviation is above 1 μm. Point C finally illustrates that for large-area masks the problem is even worse: an 800 mm plate 8 mm gives a possible error of 60 μm. It is also seen from Figure 3 that increasing the thickness of the glass plate is a weak remedy. It is impossible to increase the thickness of the 800 mm plate to bring the error down to 0.1 μm. The same is valid for the 225 mm mask in B: even a glass cube with the side 225 mm has deviations larger than 10 nm.

In conclusion Figure 3 shows the magnitude of the gravitational deformation and it shows how everything becomes more difficult for larger mask sizes.

Other errors

Clamping deformation gives a placement or registration error. Another large source of placement errors in the finished product is the distorsion in the exposure tool, be it a wafer stepper for semiconductors or a projection aligner for display panels. The maskwriter has stage errors, but these are usually well controlled after calibration to a xy metrology system, such as those made commercially available by Nikon and Leica. The placement can also be affected by processing, both because films deposited on or removed from a workpiece have built-in stress and deform the workpiece, and because some process steps cause a shrinkage or warping of the workpiece, e.g. high temperature annealing steps. An important source of errors is the pellicle used on masks. Fitting the frame to the mask plate causes the mask plate to bend.

Other effects make the size of the pattern features come out differently at different location on a mask or on a chip or display panel. There are several possible mechanisms behind this: uneven focus, non-uniform developer agitation, non-uniform photoresist thickness, uneven chrome properties on the mask and uneven film thickness on a wafer or panel, exposure dose variations in the exposure tools, effects of the time between the exposure and development or between resist coating and exposure and effect from non-perfect pre-exposure and post-exposure baking procedures. Size errors also occur because of the basic imaging properties of mask writer and the exposure station. In particular small features tend to come out too small due to finite resolution and features are affected by the presence of other features in the neighbourhood due to stray exposure. These types of size errors are also intimately coupled to shape errors, such as shortening of line ends and rounding of corners. The exact details of the mask and wafer exposure tools also interact with the pattern and create for example grid snap effects, and spurious pattern features.

Mix and match

The term used in the mask industry is "registration" which really means misregistration from a reference grid, normally an ideal mathematical grid. In the past registration of the finished product to an ideal mathematical grid has not been necessary. If all layers (approximately 25 in a semiconductor chip and 6 in a TFT) are printed using the same type of exposure station systematic and equal behaviour of the exposure stations will cancel, since every layer is distorted in the same way.

However, when resolution is pushed in order to achieve circuit speed and packing density the cost of lithography is rising rapidly, both because of higher tool cost and because of more expensive masks. To make production economical the display and chip manufacturers are trying not to use more sophisticated technology than needed for each layer, so called mix-and-match. Different layers can be printed using different types of exposure tools with different error characteristics. Furthermore the masks may be of different type, e.g. phase-shifting masks for one layer and standard binary masks on another layer. The different types of masks may require them to be written on different maskwriters.

The management of errors is made more complicated by the fact that the exposure tools for critical and non-critical layers may not even have the same exposure field. Figure 4 shows dies formed on a semiconductor wafer using tools with different fields. The critical layers like the transistor layers are printed with a tool that has a field that accommodates only one die, Figure 4a. Less critical layers, such as the top metal layers, are printed with a different stepper having a larger field and possibly a different mask reduction factor, Figure 4b. One or both of the layers can be exposed by a step-and-scan tool, and if both use step and scan they may very well have the scan direction at right angle to

each other. Furthermore, it is anticipated that in the future a single die will be exposed in two or more scanning strokes using a so called stitching scanner, Figure 4c.

In the past the thinking has been that the masks should be as close to perfect, i.e. as close to the ideal mathematical grid, as possible. Then the masks for different layers can be written on different types of maskwriters or even by different mask making companies for best economy and logistics. When all masks are exposed on the same stepper, or on steppers of the same type, the systematic errors in the stepper will largely cancel. This breaks down in the mix-and-match scenario of Figure 4a-c. The only straightforward way to resolve the complicated overlay properties of layers printed in different ways is to make each layer print an image that is close to the mathematically ideal.

The invention gives a method to predict the printing errors in a specific exposure station and correct it beforehand by predistorting and prebiasing the pattern in the opposite sense. In this application is described a practical method to manage the lithographic errors al the way to the finished product, and also in the presence of non-ideal mask blanks and clamping structures.

Object of the invention

It is therefore an object of the present invention to provide a method for predicting and correcting geometrical errors in lithography in order to achieve an improved precision.

This object is achieved with a method according to the appended claims.

Brief summary of the drawings

Figure 1 gives a projection of future lithography and the requirements on placement (registration) and size (CD).

Figure 2a shows a plate, e.g. a mask substrate. Fig 2b shows the same plate supported at two sides and the contractive stress above and the tensile stress below the neutral layer which keeps its length when the plate is bent. Fig 2c shows the lateral displacement resulting from a bent plate and how it is related to the dz/dx of the surface.

Figure 3 shows the maximum lateral displacement in the arrangement of Figure 1b as a function of plate size and thickness. The shaded areas show the resulting error.

Figure 4a-c shows dies formed on a semiconductor wafer using tools with different fields, so called mix-and-match lithography.

Fig 5 shows schematically a control method according to the invention.

Fig 6 shows flow chart describing the development of models and how the models are used to predict and correct errors.

Fig 7 shows the control method according to fig. 5 more in detail.

Fig 8 shows how the plate and/or the pattern is affected by different types of errors.

Fig 9 shows a typical implementation of an error correction system suitable for the invention using both pattern modification and writing hardware control.

Fig 10 is a schematic view of a system according to one embodiment of the invention.

Fig 11 is a schematic flow chart of the method used in the system according to fig 10.

Fig 12 is a schematic view illustrating the correction in the embodiment in fig 5 in more detail.

Fig 13 illustrates an SLM writer and a DUV stepper with a programmable mask according to another embodiment of the invention.

Fig 14a illustrates an example of a two-dimensional (2D) cylindrical CD distribution according to another embodiment of the invention.

Fig 14b illustrates an example of cylindrical CD distribution according to another embodiment of the invention.

Fig 14c illustrates an example of cylindrical CD distribution using global dose compensation according to another embodiment of the invention.

Fig 14d illustrates an example of a pre-programmed global dose map implementable using gray levels of an SLM or by utilizing dose control in a laser according to another embodiment of the invention.

Description of the invention

The invention is best described as a control system, such as is shown in Figure 5. The pattern picks up errors 501, 502 of different kinds when it is converted from a design data file 503 and a mask blank 504 to a mask 505 during a mask writing procedure 506, i.e. exposure, by means of a mask writer 507. The mask is thereafter used to produce an electronic device 508. The pattern file describes what the chip or panel designer wants to see printed and any deviation is to him an error. One part of these errors is that systematic and other errors are different from one time to another. The invention is based on the identification of different types of errors and the appropriate way to reduce each type. Errors that can be found in the output from the system and identified to be recurring in a systematic fashion are reduced by feeding an inverse error 509 back to the writing of the mask. This is the feed-back loop 510 in Figure 5. The feed-back can be pseudo-continuous, i.e. corrections are made after each written mask, or intermittently. The error is measured by a measuring means 511, and a filter 512 is useful to keep the feed-back from fluctuation with the noise component of the measured error. The low-pass filter 512 can use a very simple procedure: use the average of five measurements over five days for setting the first feed-back, then change it only when the running average over

five consecutive measurement are outside of predetermined
tolerance interval. On the other hand it can be based on
more sophisticated statistics such as time series estima-
tions and feed back an appropriately filtered correction
for each measurement of the output errors. More elaborate
statistics can be used to cancel slow changes in the
properties of the total system without ever producing a
rejected part, or to extract error components with dif-
ferent characteristics. A statistician skilled in the art
can set up statistical process control (SPC) procedures
that tunes the system without interrupting the production
flow.

In fig 12 the correction system provided in the em-
bodiment described above with reference to fig 5 is il-
lustrated in more detail. Input data is transferred to a
data collection unit 1201 in the error reduction system
506. As will be described more in detail in the follow-
ing, such input data could be one, or preferably several,
and most preferably all, of the following: pattern (de-
sign) data, blank data mask writer data, exposure tool
data, process data and metrology tool data. The input
data is then forwarded to a data validation unit 1202,
where the data is validated. The validated data is then
transferred to error prediction unit 1203 comprising a
model, for a statistical estimation of model parameters.
Correction data is then output as a position correction
map 1204 and/or a correction size map 1203, for correc-
tion of pattern element position and pattern element
size, respectively.

The correction maps are forwarded to the mask writer
507. One or both of the correction maps could be for-
warded to the data path 1206 in the mask writer 507 for
correction of the data provided from the pattern data
file, and thus correcting said distorsion. The altering
of the input design data could hereby preferably be made
in at least one processor, and preferably in several such
processors. Alternatively, or as a complement, the posi-

tion correction map could be forwarded to the position servos 1205 controlling e.g. the support table supporting the mask substrate during the writing process. In this case, the correction map implies a correction of the position control for the servo system, and thereby the position of the pattern on the substrate. Alternatively, or as a complement, the size correction map could be forwarded to an exposure dose control 1207, such as a dose modulator. Hereby, a correction of the dose according to the predicted correction map could be provided during the exposure.

There are in principle four driving forces for errors: the physical properties of the substrates on which the patterns are printed, i.e. the mask blanks and the wafers or panels, the position on the substrate, the exposing equipment (which can be using electromagnetic radiation or particle beams as the exposing medium) including exposing sequence and environment, and the pattern itself. These driving forces interact with each other directly of via the production processes to create errors. An important feature of the invention is the use of models to translate measured or previously known physical parameters to a placement, size or shape error to be corrected. An example is a plasma etcher. The plasma is non-uniform towards the edges of the substrate and in local areas where the surface exposed to the plasma is different from other places in the pattern. This creates a position- and pattern-dependent size error. It can however be characterised with a small number of parameters, such as an edge fall-off magnitude and typical length, and a sensitivity and disturbance length for pattern variations. Using this model with four parameters it is possible not only to precompensate for the edge fall-off, which is equal from plate to plate, but also for the local variation which vary with the patterns.

Using a model-based error prediction makes it possible to account for a large number of different error

mechanisms with a manageable amount of empirical data collection. Designing sampling and measurement plans that effectively fit the parameters of a model from a limited number of measurements is known in the art, and can be found in textbooks on experimental design. It is also known how to design plans to separate between different driving forces. The ideal situation is that measurement are made non-destructively on production masks and wafers, but for a specific model it may be more efficient to use a special monitor substrate, i.e. to be able to distribute a matrix of test structures over the entire surface.

The model-based error prediction is further described in Fig 6. Two different mechanisms for generation of errors are set up, e.g. edge falloff and pattern dependent etch activity in an etch step. A measurement is designed which can find the parameters for each and separate between them. In this example it can be measuring features in areas with three densities each at three locations, inside, intermediate, and close to the edge of the substrate. The measurement is done and the parameters extracted. Before writing and correcting a pattern relevant information has to be collected in this case the pattern density in different areas of the pattern and the distance of pattern areas to the edge of the substrate. The total correction is generated, in most cases by superposition of the corrections for the two mechanisms, other times by a more complicated summation.

Another aspect of model-based error correction is shown in Figure 8, namely decomposition of complicated error behaviour into a set of independent and computable error mechanisms. The general geometrical error in a mask writer is very complicated, but it can be decomposed into isotropic expansion, built-in shape, gravitation sag, clamping deformation due to non-ideal geometry of the clamping structure, and interaction between the built-in shape and the clamping geometry. If each error is small,

which is the case for lithographic substrates, the con-
tributions can be superposed. On top of it come the stage
errors, i.e. errors in the coordinate system of the
writer.

An important case of model-based error correction is
when a chip has a CD error towards the edge, for example
due to stray light. If a 0.18 feature is 3% percent too
small one would expect that a + 3% size correction in the
mask would compensate it perfectly. However, due to the
finite resolution of a stepper there is a more compli-
cated function relating size on the mask to size on the
wafer, the so-called "Mask Error Enhancement Factor",
MEEF. The enhancement factor is size dependent and de-
pends on the details of the tools and process. Therefor a
model need to be used that takes the MEEF into account,
and the corrections will not be correct until the MEEF
model has been verified a couple of turns around the
feedback loop.

Process errors 502, if they can be held constant,
can in principle be corrected with the feedback loop.
Other errors 501 are impossible to correct by feedback,
because they are not constant in time. In the invention
one important such error has been identified as the
clamping distortion of the mask in the mask writer, the
metrology system and in the exposure station that uses
the masks. At first sight the clamping errors seem uncon-
trollable, but we have found that they can be predicted
from accurate geometrical data for the mask blank itself
and the clamping structure of equipment using or operat-
ing on the mask. Another seemingly random error source
that is controlled in another embodiment of the invention
is variations in linewidth due to variations in resist
and chrome properties over the mask substrate. Using the
invention it is possible to set up and apply models for
how the resist thickness and chrome properties affect the
feature size of the pattern and correct for the errors
created.

Since these properties are possible to measure by measuring means 513, 514 prior to the writing of the mask, it is possible to predict the errors and correct them at the time of writing the pattern, the feed-forward correction loop 515 in Figure 5.

Residual errors

By the feed-forward or feed-back correction 509, or especially a combination of the two, a large portion of the total errors can be controlled and corrected. The residual errors are due to random errors during maskwriting, exposure and processing, and have to be addressed as such, i.e. by better temperature control, vibration-insulation, process automation, etc. They are also due to incomplete error models and uncertainty in the model parameters. We believe that when the framework of the invention is established there will be a development of better and better models until eventually all but the genuine noise errors are removed. The development of models and software for their characterisation and use could well become the mission of independent commercial companies.

A flow chart describing the development of models and how the models are used to predict and correct errors is given in fig 6.

A comprehensive list of error sources

Figure 7 shows the work flow from glass block and CAD file to a finished chip or TFT display, and important error mechanisms that can be modelled and corrected. The work flow is divided in three separate parts of making the mask blank, writing the mask on the blank, and finally using the mask for lithographic production, and each part is divided in several different steps. For each step is further indicated different types of errors possible to occur during said step. These errors are however merely examples of errors possible to occur during each

step, and many other errors are probably possible as well. As is described above, errors in at least some of the steps are measured and used either in a feedback or a feed-forward loop to predict the error in the written pattern, and to generate corrections to compensate for said predicted errors during the exposure step in the mask making.

Correction of clamping errors

If is held in exactly the same way during writing and use there is no error. Until now it has been possible to treat the semiconductor mask as a stiff plate with no deformation induced by clamping, provided that the clamping has been done carefully. There are two developments that make the clamping-induced deformation more critical in the future: increased mask size and dramatically tightened precision requirements. The new mask format of 225 x 225 x 9 mm has been defined and the allowable geometrical errors in a mask will be 30 nm in 2001 and below 10 nm a few years later. The registration error allowed is typically 5% of the features on the photomask and the error of critical dimensions (CD) must be less than 2.5%. Current plans for lithography predict that the features will be around 25 nm in the year 2010. With a reduction ration of 4 the features are 100 nm on the mask and the registration requirement is then 5 nm and the CD tolerance 2.5 nm. A few years later the requirements are predicted to be sub-nanometric if the march toward smaller scale were to continue. Mask production following what is known in prior art cannot produce masks to these requirements. In the invention methods are devised that can reduce many systematic errors by an order of magnitude or more.

It is known in prior art to support the glass plate at three points. With three supports there is no bending induced by the supports. Therefore it deforms only under gravity. It is also known to correct the pattern geometry

for the computed deformation due to the gravitational sag
when it is supported on three supports. The deformation
depends only on the plate size and its material proper-
ties and can be computed beforehand.

In flat panel production the masks may be 600 x 800
x 12 mm. It is not possible to support such a large plate
on three points and get a sufficiently flat surface. The
plate needs to be supported at more than three points and
becomes kinematically over-constrained. The supporting
structure will introduce deformations if the points are
not in a perfect plane. In this case the deformation is a
combination of gravitational sag and deformation due to
the support structure. The same applies to a co-ordinate
measuring machine where the plate needs to be measured
without distorsion.

The basic problem is that due to technical con-
straints different machines producing and using a pat-
terned workpiece hold the workpiece by different meth-
ods,: For example a reflection-type metrology system for
semiconductor reticles normally uses a three-point sup-
port with the support points chosen for minimum deforma-
tion, but the stepper using the reticle must support it
along the edges to keep the patterned area unobstructed
for the exposing light.

If the workpiece or the clamping structure is non-
ideal, i.e. non-flat, the different types of clamping in
different types of equipment give an uncertainty in the
geometry of the workpiece.

A numerical example: assume that a standard semicon-
ductor reticle (152 x 152 x 6.25 mm) is supported at the
four corners. One of the corners is 1 μm out of the plane
of the other three corners, either because the glass is
non-flat or the supporting points are skewed. The bending
of the glass causes a line along one diagonal of the
plate to be stretched and the other diagonal to be com-
pressed. This is the same as an orthogonality error in
the pattern on the mask with a maximum lateral position

error on the plate of 0.5 μm * 6.25/2 mm / 152 mm = 20
nm. The error from the clamping must be added to other
error sources such as drift, scale errors and effects
from the process. Therefore 20 nm is unacceptable as an
error from the clamping alone. And if the points were lo-
cated closer together or if there were more than four
constraining points the errors would be even larger. We
have found that supporting a plate on four well chosen
points is exceptionally good for large plates, giving a
deflection that is 20 smaller than with htree support
points. The invention makes it possible to use four
points and compute the effect of the plate being overcon-
strained. If the flatness in force-free state is known
and the height of the upper surface is measured at the
four point one has all necessary information to correct
the pattern for bending and gravitation.

The invention devises a method for complete predic-
tion of the clamping errors as well as partial correction
for stress-induced errors in a multi-machine environment
with equipment for writing masks, printing panels or wa-
fers from masks and metrology systems for measuring
masks, wafers and panels.

Description of a preferred embodiment

The mask blanks are cut and polished by a glassmak-
ing company. The surface figure is controlled to a maxi-
mum error corresponding to a quality class of the glass
product. The glass plate is coated with a sputtered film
of chromium and a photoresist coating is spun on. In the
preferred embodiment of the invention the flatness of the
front and backside of the glass is measured before and
after the coating with chrome and after the resist coat-
ing. A flatness map is generated for each side together
with other auxiliary information such as the exact thick-
ness and the Young's modulus of the glass material. Each
glass plate has a serial number engraved at the perimeter
of the chrome surface before the chrome coating so that

the identity of the plate can be tracked through-out it's lifetime. The serial number is engraved in the glass surface or chrome film in clear text and machine-readable format, e.g. by laser ablation. It is also possible to laser engrave an identity mark inside the volume of the glass or use other marking methods such as magnetic recording in the chrome coating or embedding of a memory devise in the glass plate. Identification of semiconductor wafers by an engraved marking is standard in the semiconductor business, and in the invention the same would be applied to mask blanks. Any other secure identification system can be used, for example storing and shipping the mask blanks in marked and bar-code labelled boxes.

The mask blank maker stores the flatness data for each blank on a computer and the data is published on a network accessible to the mask makers at a later time, e.g. on an Internet server. Alternatively the data could follow the blank, e.g. on a diskette shipped with the blank or on the embedded memory device.

How to measure the flatness and other properties of the mask blank is known in the art. Flatness is often measured by interferometers made by for example the companies Möller-Wedel, Zygo and Tropel. The resist thickness can be measured with spectroscopic reflectometry, ellipsometry and other optical methods. The chrome thickness can be measured by optical transmission or inductive methods and the reflectivity of the chrome layer by reflectometry. The exact thickness can be measured with mechanical or optical methods.

When a mask or reticle is ordered by a semiconductor company the specification includes the serial number of the stepper for which the mask is written. The clamping system of each stepper is characterised by a file of geometrical data describing the method of clamping, but also and most important the individual imperfections of the clamping system. This information is stored on a network

accessible to the mask maker or sent to the mask maker together with the order. The mask maker can also pull information about the process, e.g. uniformity data for a etching step from the semiconductor manufacturers computer. Alternatively the data can be attached to the order document as embedded data or as separate documents.

The mask maker who typically have several mask writers of different kind have a similar database of data for his writing systems and processes. He also has empirical data of how the mask is distorted by the application of a pellicle, the stretched film that acts as a dust protection on the finished mask.

When the chrome and resist were applied at the mask blank manufacturer the blank bent due to stress built into the films. When the resist is removed during processing in the mask shop the stress from the resist disappears and the blank goes back to the state it was before the resist was applied. More important is that when a pattern is formed by partial removal of the chrome the stress from the chrome film is partially relieved. With knowledge of the bending caused by the application of the chrome film during manufacture and the pattern to be written it is possible to predict the deformation of the plate by patterning of the chrome.

During the planning of the writing job the mask maker fetches the applicable information for the stepper or exposure station in which the mask will be used, for the maskwriting equipment, for the blank and for the pattern. Using the error model a total combined error can be computed and corrected for, optionally using the MEEF factor or a similar function as a transfer function from correction to result in the finished pattern. In another application of the invention the collected information can be used to select among mask blanks, writing systems and processes. A simple example is the selection of blanks for uniformity for patterns that occupy different areas on the mask. Of course, the principle of the

invention is the same whether the end result ("the output") is a chip, a display panel or just the mask.

This contains geometrical information about the clamping geometry, imperfections of the clamping structure and also other known image distorsion created by the tool and subsequent processing.

The maskwriter

In a preferred embodiment the mask writer has several provisions for correction of distortions caused by the processes chain from patterning to use. First it has a precision stage controlled by laser interferometers with a adjustable scales in x and y, corresponding to uniform shrinkage or expansion plus uniform bending across each axis, such as may result from built-in film stress. Secondly it has adjustments for orthogonality and trapezoidal distorsion, by modification of the driving of the servos servos and by software. For higher order errors such as barrel distorsion, mirror bow and irregularity of the coordinate system, the maskwriting machine has an xy correction map that sends position-dependent offsets to the servo systems. The information collection and error prediction system sends a uniform scale and an xy map to the maskwriter for each mask to be written, said map being the pattern correction necessary to correct for all known errors. These of course include the maskwriter's own stage errors.

Furthermore the maskwriter has a clamping structure that is adapted to the particular type of mask blank to be written. In one embodiment the plate is placed on three supports so that the deformation of the plate in the maskwriter is independent of the plate shape and can be computed easily. For the most accurate correction the supports are placed identically to similar supports in the equipment using the mask, e.g. near two adjacent corners and at the center of the opposite side.

In many cases it is not possible to support the mask
plate at three points. Especially for larger-size masks
it is necessary to have more than three supports. In this
case it is impossible to hold a mask without introducing
bending moments, if not both the support structure and
the plate are perfectly flat. In one embodiment the
forces exerted on the supports from an ideal
plate/support structure combination are derived theoreti-
cally and the geometry of the supports is adjusted until
the force on each support matches the theoretical force.
In another embodiment the non-flatness of the plate is
known beforehand and the geometry of the clamping struc-
ture is modified so as to minimise bending forces. Other
deformations such as that from gravitational sag and sub-
sequent process distortion are computed and corrected
for.

In another embodiment the support structure is not
adjustable but geometrically characterised, so that it is
possible to compute the bending of a particular plate re-
sulting from the combination of plate non-flatness and
clamping geometry.

In another embodiment the maskwriting system itself
is adapted to measure parameters that are needed for the
correction, such as the flatness of the substrate. If the
flatness is measured after clamping in the maskwriter,
the measured data can be used in several ways. First it
can be used to check the model of the clamping structure.
Secondly it can replace the detailed knowledge of the
stage flatness, since the exact form and the clamping de-
formation can be calculated from the surface flatness
combined with flatness data of the substrate. In the case
that there is no flatness data available and the plate is
known to be flatter than the stage and/or the gravita-
tional sag, the measured deviation from flatness indi-
cates a real deformation and can be used for an approxi-
mate correction.

A measurement of other parameters such as resist thickness can also be integrated with the maskwriter, to provide information necessary for the correction independent of the mask blank maker or to be used with in-house spun plates.

The invention can be used in different types of maskwriters using scanning laser beams, spatial light modulators or particle beams.

Exposure station

Like the maskwriting equipment the exposure station or stepper that is going to use the mask to print the pattern on a workpiece has a number of errors, such as image distorsion in the exposure step and warpage in the subsequent processes. In a preferred embodiment the mask is supported by three supports and the clamping gives no additional bending forces beside the gravitational sag. In another preferred embodiment other design constraints makes it necessary to clamp it kinematically over-restrained, i.e with more than three support points. The pattern distorsion due to the bending forces resulting from imperfect geometry can be cancelled by modification of the clamping structure as in the maskwriter or by pre-diction and precorrection of the mask.

The geometry and the errors of the exposure station are characterised and stored as a machine parameter file, which contains enough information to compute the errors of a real physical mask and how it is printed. The file may, apart from the identity and bookkeeping information, contain, the number of supports, their xyz coordinates and compliances and optional springloading, further distorsions of the machine's coordninate system etc.

It is also valuable to have a process distorsion file which contains an error map for how an exposed work-piece is distorted by subsequent processing. An example is a glass panel for a TFT-LCD display that may shrink by several tens of ppm in high-temperature steps.

Metrology tools

The masks and the exposed workpieces are measured in coordinate measuring system, such as those commercially available from the companies Leica and Nikon. The metrology tools also have a clamping geometry and built-in errors that can be described in a machine geometry file. Even though the metrology tool does not impose its errors directly to the mask, it does so indirectly by being the reference against which all other systems are calibrated.

Computing the bending forces

A mask blank has a simple geometry and is made from high-quality quarts or glass. Therefore, it can be represented by a simple finite element model as is well known to a person skilled in mechanical design. All errors are small compared to the size of the plate and the resulting errors can be computed by linear superposition of distorsions from different sources, e.g. gravitational sag and bending due to clamping are additive. This allows for simplified methods of analysing the elastic glass plate by decomposition of different bending modes. This is advantageous for real-time correction on an embedded computer in the mask-writer, but it is equally possible to run a full finite element simulation on an embedded computer with adequate memory and power, or at an offline workstation.

Given a machine parameter file, with the geometry of the supports and the orientation of the force of gravity relative to the plate, and a plate parameter file with the geometry, flatness and elastic properties of the plate, the computer can use the finite element model to find the shape of the plate, the distorsion of a pattern on its surface, and the contact forces at the support points.

If there are many support points it is not known beforehand that a particular non-flat plate really makes contact to all supports. It is, however, possible to find

which points make contact. In principle the solution has
to be self-consistent. The plate makes contact to a sup-
port point if there is a positive contact force, includ-
ing the effect of possible spring-loading. By this method
it is also possible to find the approximate area of con-
tact between the mask blank and a flat surface, e.g. a
flat stage top, by representing the flat surface by an
array of contact points.

Because of the linearity of the elastic plate and
the simple geometry it is also possible to derive a sim-
plified set of simultaneous linear equations describing
the deformation of the workpiece due to forces at a num-
ber of predefined positions on the workpiece. Other posi-
tions can be treated by interpolation between the basic
computational points. The system of equation is solved
for the geometrical constraints given in the geometry
files and the bending forces are derived. These are added
to the gravitational sag that depends only on where the
support points are placed.

Correction of other mask blank related errors

Other properties of the mask blank affect the qual-
ity of the image, such as the resist thickness, the
chrome thickness and the reflectivity of the chrome.
These can be measured in the same way as the flatness or
in fact in the same equipment.

Implementation of the correction

Once the errors are predicted and the appropriate
corrections are computed there are two principally dif-
ferent methods to apply them. Either the pattern data is
modified, e.g. the corner points of each feature are
moved, or else the corrections are fed to the writing
hardware, such as position servos for placement and modu-
lator or light source for intensity control. The former
method is more general and can in principle give arbi-
trary large corrections. It is also the only possible al-

ternative for shape corrections involving serifs and
similar features. For small and slowly varying correc-
tions the second method gives a smoother correction,
since it has the resolution of the interferometer while
modification of the data only has the resolution of the
address grid. A second advantage is that the data can be
prepared offline without knowledge of the mask blank and
machine specifics and the corrections applied at the time
of writing. But for very dense patterns the data prepara-
tion has to be done in real time anyway, so there is lit-
tle difference in logistics whether the correction is ap-
plied to the pattern or to the writing hardware. Correct-
ing the pattern is perfectly flexible: corrections can be
applied for placement, size and shape and there is no
limit to the size or complexity of the corrections.

Real-time pattern correction

With a real-time data path with high processing ca-
pacity it is possible and advantageous to apply correc-
tions for beam size or resolution effects and stray expo-
sure together with all other corrections at the time of
writing. In a typical implementation there is a bank of
parallel processors, possibly organised in groups doing
different steps of the data preparation, with up to sev-
eral hundred CPUs and ASIC:s. The slowly varying correc-
tions, e.g. for clamping distorsion, will not effect the
work load or data flow appreciably, but corrections for
resolution, beam size and stray effects generate immense
amounts of extra data and require processing capacity to
match the data flow. However, there is an big advantage
to real-time correction and for exactly this reason. The
data volumes are difficult to handle with off-line cor-
rection. In a commercial mask shop where a maskwriter is
running essentially 24 hours a day, there is also no cost
benefit of doing the correction off-line, since an
equally powerful computer is needed to furnish corrected
data to the maskwriter at full writing capacity.

The general concept of pattern correction to compensate for the limited resolution is known in the prior art. In the invention the correction is done in real time as a part of the real-time processing. For real-time correction of resolution, beam size and stray effects the algorithm is preferably running on the maskwriter's embedded processor bank. The control system supplies only the parameters for the interaction between the image formation and the pattern, e.g. a series of superposed gaussian profiles representing the point-spread function or the beam of the writer and exposure system, or a system of rules for the correction. A typical rule is to add a 0.16 ▯m serif to all outer corners in the pattern.

Correction of the imaging properties of the maskwriter is preferably done transparently, with parameters that are fitted to that particular maskwriter and process but otherwise not changing. Once the parameters are set up the user will not need to care, or even know, about the correction, but will only see a mask pattern with a more accurate representation of the input data.

Pattern correction for the exposure station is preferably done in collaboration between the mask shop and the chip or panel manufacturer. The manufacturer prints some test patterns that are designed for extraction of the model parameters. Once the model parameters are set the correction could be transparent and automatically applied to all designs. The information system of the invention pulls the parameters together with clamping data and image distorsion when the writing job is set up. Or alternatively the manufacturer would explicitly provide another set of correction parameters, or correct the data directly using his own correction model. However, we believe that the design of image correction models, design of test patterns and extraction software will be the mission of specialist consulting companies, and that the manufacturer will use the system in the transparent mode. The information system of the invention provides the

framework, which makes such transparent operation possible and convenient.

Figure 9 shows a typical implementation of an error correction system suitable for the invention using both pattern modification and writing hardware control. The writing hardware 901 prints a pattern 902 on the mask blank 903 using a low-level representation of the pattern 904, e.g. a bitmap or a decomposition into small area elementary forms such as trapezoids. The low-level format is created from a geometrical database with a high-level input 905, containing a geometrical description of the pattern, such as a list of filled polygons. Since the input format can contain the geometrical features in any order and they can have any shape they are pre-processed into an intermediate format 906 after having been distributed 907 from the external file interface 913 on a number of parallel processors 908. For each conversion step the data volume expands and the necessary processing power increases. Therefore the final processing needs more parallel processing units 909 than the pre-processing. The error correction system has a control unit that predicts the errors from the collected error data and computes an appropriate pre-compensation based on its set of models and rules. The correction of small slowly varying size and placement errors is sent 912 to the writing hardware, especially to the dose control and the position servos. Pattern corrections are sent in the form the correction rules to the datapath interface 913 and run on the embedded computer banks 908 and 909. Even the pattern corrections can take different forms and several correction algorithms can be run at different conversion steps. For example, correction for the beam size effects in the mask generator is suitable to run at the last stage of the conversion, while the larger serifs needed to compensate for the imaging effects in the stepper are added to the pattern during the pre-processing step.

For efficiency it is suitable for the different processors to work on separate areas of the pattern, but to apply corrections for non-local imaging effect the processor needs to know the pattern in an area around the actual point it is working in. Therefore the pattern is cut into partly overlapping computation fields. The redundant information is only used for the correction and discarded after use. For faster processing of non-local information, e.g. for correction of stray exposure, a temporary representation of the pattern at a lower resolution is created and used to compute background exposure. It is possible to use more than one low-resolution representation at a single time to represent phenomena at different length scales.

In one embodiment the two processing steps are complemented with a third step that runs on a separate bank of processors essentially dedicated to pattern correction.

In a preferred embodiment of the invention two correction maps are computed, one for position and one size. The position map has the form of a table with x and y deviations given at a grid of points. For a given stage position the corresponding s and y correction is computed by interpolation in the correction map and the result is fed as an offset to the position servos. The same method is used for finding the correction of CD errors by interpolation in the CD map.

In a different embodiment the correction maps are computed and made available to the datapath. During the conversion from pattern database to hardware-driving signals both position and size is corrected. In the preferred embodiment, which has a stripe-organised writing strategy, it is done at the fracture step, just before the pattern is divided into strips. The vortex points of the pattern elements are simply moved according to the interpolated correction maps. Most pattern elements have edges parallel to the axises, and would after the correc-

tion have slanted lines, but since the scale of the corrections is normally of the order of a part per million or less, all but a few edges are still parallel to the axises after their coordinates have been truncated to the resolution of the data preparation software, e.g. 0.1 nm. Before writing they are further truncated to the address grid of the writer, e.g. 4 nm for semiconductor reticle at a specific specification level. The written pattern will have the smooth curves of the correction map snapping to the address grid, but with an appropriately chosen address grid this will give a negligible contribution to the error statistics.

The information system

An information system is built to manage the lithography errors in the chain from mask blank maker to user of the final products. The hub in the information system is the mask maker where during job planning all information is collected and used to predict errors and pre-compensate them.

A convenient way to organise the information when several parties are involved, e.g. mask blank makers, mask shops and mask users, is to have each party maintain its own information and store it on its own computer system. The computers are accessible from the mask maker's computer by remote access over phone line, ISDN, high-speed link or the Internet. In the latter case it is important that the integrity of the information is validated, so that the user of information knows it is complete, unaltered and issued by the correct sender. The parties involved may also want to have it confidential. All this can be assured in modern communication links by appropriate use of passwords, encryption, check figures and digital signatures.

Workflow

It is the responsibility of the mask shop to find the necessary corrections that will make a particular reticle print without systematic registration errors. The customer, i.e. the mask user, provides one or more pattern files and the order document requests any special treatment, metrology etc. In a preferred embodiment of the invention the order document specifies the exposure station where the mask will be used and optionally also a process error description. During job planning and set-up the mask maker's computer accesses the data from the mask user, data which specifies the geometry of the exposure station, including known imperfections, and image distorsions. Optionally the machine file also includes a map of size errors created by the exposure step. If a process file has been specified in the order document, it specifies warping of the workpiece during subsequent processing and optionally also size errors created by the process. For example a plasma etching step is sensitive to the "loading", i.e. the local density of pattern area exposed to the plasma, and etches differently along the edges of a chip. Since this is a systematic behaviour that is repeated more or less in every design it can be partly corrected for in the mask using information about said mask.

When the writing job is planned a mask blank is assigned to the mask. The computer accesses the data storage at the mask blank maker or a local storage with information files for the blanks that are in stock. The information file fetched corresponds to the particular mask blank that will be used for writing the mask, and holds information about the exact size and thickness as well as relevant physical material properties. It also contains flatness data, resist thickness, chrome thickness and reflectivity and data relating to the bending force created by built-in stress in the chrome and resist. The scheme is, of course, independent of the exact materials used,

and other types of existing or future mask blanks can be handled in a similar fashion.

Data file formats

The data file formats are designed to be extendable by having the data fields tagged with keywords. A new feature can be included after definition of a new keyword and old data files will still be compatible. For simplicity the data files in the preferred embodiment are ASCII character files. This allows for simple debugging and files can be modified or created in any text editor or spread-sheet program. To avoid the risk of inadvertent change of a file it is locked by a checksum and validated by a digital signature. For machine-generated files these are generated automatically, but hand edited files need to get the checksum and signature added by a special validation program. This gives a reasonable trade-off between security and flexible engineering and debugging. For encryption any commercial encryption program can be used.

Example of a system using an embodiment of the inventive method

A system for producing large-area displays with distortion control according to an embodiment of the invention should now be described more thoroughly.

Referring to fig 10, an embodiment of the system for producing large area display panels according to the invention is shown. The system could be used for producing shadow masks for conventional CRT (Cathode Ray Tube) displays, but is especially useful for producing TFT (Thin Film Transistor), CF (Color Filter), PDP (Plasma Display Panel) or PALC (Plasma-addressed liquid crystal) displays.

The system comprises a first mask producing means 1001 for producing a mask with a predetermined pattern according to input data. The mask producing means is

preferably a microlithographic writing device for writing
with high precision on photosensitive substrates. The
term writing should be understood in a broad sense, mean-
ing exposure of photoresist and photographic emulsion,
but also the action of light on other light sensitive me-
dia such as dry-process paper, by ablation or chemical
processes activated by light or heat. Light is not lim-
ited to mean visible light, but a wide range of wave-
lengths from infrared to extreme UV. Such a mask produc-
ing apparatus is previously known from e.g. EP 0 467 076
by the same applicant. In general the apparatus comprises
a light source, such as a laser, a first lens to contract
the light beams, a modulator to produce the desired pat-
tern to be written, the modulator being controlled ac-
cording to input data, a reflecting mirror to direct the
beams towards the substrate, and a lens to contract the
beams before it reaches the substrate. The mirror is used
for the scanning operation to sweep the beam along scan
lines on the substrate. Instead of a mirror, other scan-
ning means may be used, such as a rotating polygon, ro-
tating prism, rotating hologram, an acousto-optic deflec-
tor, an electro-optic deflector, a galvanometer or any
similar device. It is also possible to use raster scan-
ning or spatial light modulators. Further, the substrate
is preferably arranged on an object table which has a mo-
tion in two orthogonal directions relative to the optical
writing system, by means of two electrical servo motors.

The system according to the invention further com-
prises microlithographic exposing means 1002 for exposing
a photosensitive panel substrate with light and with use
of the mask to impose the pattern of the mask on the sub-
strate, whereby said substrate has a layer being sensi-
tive to said light. Several such exposing means are also
previously known in the art. The exposing means could be
of the contact copy type, proximity exposure type, or a
projection aligner. The system according to the invention
could also be used in a direct writer, whereby the com-

pensation is not made in a physical mask, but in a data mapping controlling the writing beam. For TFT and CF display panels projection aligners are usually used, and for PDP and PALC the contact or proximity type are frequently used.

Furthermore, the system comprises measuring means 1003 for measuring the pattern on the substrate and detecting deviations relative to the intended pattern as given by the input data. This could be done by measuring the geometrical position of the pattern, preferably at some reference positions, to get a so called registration mapping, and compare it with the intended pattern which is deducible from the input data. Further, the width of lines in the pattern, the so called CD (Critical dimension), could be measured. Measuring equipment is commercially available, and for example the equipment could comprise a CCD-camera or be based on interferometry.

From the measuring means 1003 a distortion control signal is sent to a second mask producing means 1004. This second mask producing means could be a separate apparatus, but is preferably the same as the first mask producing means 1001. This second mask producing means is fed with input data describing the intended mask pattern to be written, and is also fed with the distortion control signal from the measuring means 1003, whereby the writing process for producing the second mask is controlled to modify the pattern to compensate for the measured deviations, and thus compensate for production distortions. The measurement is preferably made after the subsequent processing steps of the panel as well, i.e. the development, blasting and/or etching, whereby systematic errors from theses processes are taken care of in the compensation as well.

The compensation in the mask writer could be accomplished in different ways. In a writer of the type described above, with an object table continuously moving in a slow strip direction and a scanner sweeping in a

fast scanning direction, the compensation could be made according to a surface mapping. According to this mapping the compensation in the scanning direction could be accomplished by e.g. offsetting the starting time of the beam during the scanning. In the stripe direction the compensation could also be made by time offsets, either directly or indirectly by means of different ramp functions. There are also other possible way to accomplish such compensation. For example the compensation could be made by controlling the servo motors for the object table, by adjustment of the time dependent angle of the scanners, by changing the input data or by controlling an internal control unit such as piezoelectrically controlled mirrors.

However, if a direct writer is used, the same type of compensation could be made in real time.

Compensation for deviations in the line width, CD, could be accomplished in the same way as deviations in the registration. However, this compensation could also be made by changes in the power of the writing beam, i.e. the exposing dose, by changing the laser output or having an analog modulator. This compensation could be accomplished by means of a herefore adapted dose mapping to control the dose.

When the second mask is used in the same exposing means 1002 all systematic errors depending on different temperature conditions, errors in the exposing means etc., are compensated for, and the pattern precision of the produced display panels are greatly improved.

The first mask could either contain the same pattern as the intended pattern for the second mask, i.e. the pattern not being compensated, or contain a reference pattern, intended for deviation measure only.

Further, error data could be accumulated, and a rolling means value could be used for the compensation. The error compensation could also be a combination of several different part error compensations. Those part

compensations could be based on the premises for the process, e.g. which stepper and type of glass that is being used. Hereby the total error compensation could be a combination of one or several error compensations for each process step.

Above, a system for passive distortion control has been described. In this system compensation is made for the processes and equipment being used in the system. However, the compensation is not adapted for different panel substrates. In this passive system a measurement to alter the distortion compensation is preferably made once for every new batch of substrates, and thereafter the same mask is used for producing all the panels in the batch. This passive distortion control is specifically useful for production of TFT or CF displays. The requested precision for the patterns on the mask for this production is extremely high, and the masks are very difficult, and thereby expensive, to manufacture. On the other hand the masks last for a long time in this production.

The system according to the invention could also comprise second measuring means 1004 for measuring the thickness of the light sensitive layer on the substrate prior to the exposure, whereby said measurement is also used for said compensation. Hereby the compensation is adapted for varying resist layers between different batches of substrates. Such batch wise compensation could also be accomplished with use of data specified by the manufacturer.

This second measuring means 1004 could also be used for measuring each and every panel substrate that is going to be exposed, and thereafter adapt the process for each individual panel. Hereby the system could compensate for varying glass quality in different panels, varying thickness and quality of the resist or emulsion of the substrate area, different form variations etc. This active distortion control is especially useful for produc-

tion of PDP or PALC display panels, where the masks are comparably easy and inexpensive to produce. This method could also be used for direct writers.

In the active distortion control the panel is initially measured, regarding e.g. resist thickness. Many such measuring methods are available for someone skilled in the art, e.g. a test exposure, dosimetry, of the substrate with different doses, by profilometry, interferometry, confocal microscopy, by an interferometric method or the like. The shape of the substrate could also be initially measured, and this could be accomplished by known methods such as moiré interferometry, projected fringes, laser triangulation, ordinary interferometry etc. Preferably already existing patterns are also initially measured, whereas such exists. Display panels are usually exposed in several separate steps, typically 3-7 exposing steps, and normally the same exposing station is used for all the exposures. By writing masks with compensation for individual errors in different station the display producer could schedule the production more freely, independent of which stations that is used. This is of great importance for making the production more efficient and the utilisation of the stations better.

Referring now to fig 11, a method for producing large area display panels according to the invention, and with use of the above-mentioned system will be described.

The method according to the invention comprises a first step S1 in which a mask with a predetermined pattern according to input data is produced. Thereafter the mask is used for microlithographically exposing a photosensitive substrate with light to impose the pattern of the mask on the substrate, whereby said substrate has a layer being sensitive to said light, in step S2. The exposed pattern is then measured, possibly after several subsequent processing steps, or even in the finished product, in S3, to detect deviations of the exposed pattern relative to the intended pattern as given by the in-

put data. In step S4 a distortion control mapping is then produced, to be used in step S5 during production of a second mask having a pattern according to input data and modified to diminish the measured deviations, and thus to compensate for production distortions. In the last step S6 the second modified mask is then used in a photolithographic fabrication of display panels. Similar compensation may be used in a direct writer, where the compensation could be made in a data mapping.

Dose Compensation

CD uniformity may be an important specification for photo masks. A final result may be a combination of pattern generator equipment uniformity and process equipment uniformity.

After exposure of a mask in a pattern generator the resist covered plate may be processed in different process systems, e.g., hot plate, development equipment for resist, and etching equipment for chrome. The process equipment steps may introduce systematic CD variations on the plate, e.g., cylindrical symmetry, due to the physical design of process equipment.

If the CD contribution from process equipment is stable over time the overall result of CD uniformity on the final mask may be improved by introducing a CD correction of opposite sign, (process compensation), in the pattern generator while printing the plate.

As described above in detail above, process compensation in a pattern generator may be generated directly in the data path used for pattern generation by modifying the printed pattern itself. As also described above, alternatively, process compensation in a pattern generator may be generated indirectly by changing other global parameters as, e.g., exposure dose while printing the plate. For example, CD may be a function of dose.

Writing principle, SLM writer

An SLM writer may operate as a DUV stepper with a
programmable mask. Hence, a full image may be generated
as series of 2D projected SLM stamps, where each SLM
stamp may be printed with a separate laser flash of short
duration. Multi pass printing including offset between
passes may be used that substantially reduce systematic
CD errors over the SLM stamp.

Global CD, may be corrected with a dose system, us-
ing a dose map, as each individual SLM stamp is small
compared to the full 6" plate.

As shown in Fig. 13, a dose map as a function of xy-
position on the mask may be generated, e.g., by using the
gray levels of SLM or by using a pre-programmed global
dose profile utilizing the dose control in the laser.
During the exposure cycle the x-stage may move at con-
stant speed. As shown in Fig.13, one or more interfer-
ometers may generate trigger pulses at correct positions
and act as a master trigger in the system.

Both the data path/SLM and the laser may be
controlled by this master trigger. Process compensation
using a dose map(x,y) may be implemented using the SLM or
laser dose control.

Fig 14a illustrates an example of a (2D) cylindrical
CD distribution according to an embodiment of the
invention. As shown in Fig. 14a, no dose compensation is
provided.

Fig 14b illustrates an example of cylindrical CD
distribution. As shown in Fig. 14b, dose compensation is
provided and CD is compensated.

Fig 14c illustrates an example of cylindrical CD
distribution using global dose compensation. As shown in
Fig. 14b, dose compensation is provided and CD is
compensated.

Fig 14d illustrates an example of a pre-programmed
global dose map implementable using gray levels of the
SLM or by utilizing dose control in the laser.

As set forth above, example embodiments of the present invention may improve precision by predicting and/or measuring errors and correcting the errors. As also set forth above, example embodiments of the present invention may improve precision by compensating directly in the data path used for pattern generation and/or compensating indirectly by changing other global parameters, such as, e.g., exposure dose. As also set forth above, example embodiments of the present invention may improve precision by maintaining correction information in a correction map or correction profile.

The invention shall not be limited to the embodiments described above, which are only examples of implementation. For example what is said above about chrome-on-glass masks is equally applicable to masks made from other materials, e.g. with coatings of other metals, iron oxide, diamond-like carbon, multilayer coatings etc. , and with other substrate materials such as calcium fluoride, Zerodur, silicon etc, as well as for both transmissive and reflecting masks and masks which work by scattering. It is also applicable to stencil masks and membrane masks for particle-beam and x-ray lithography.